Harnessing scalable open source packages for magnetic confinement fusion modeling

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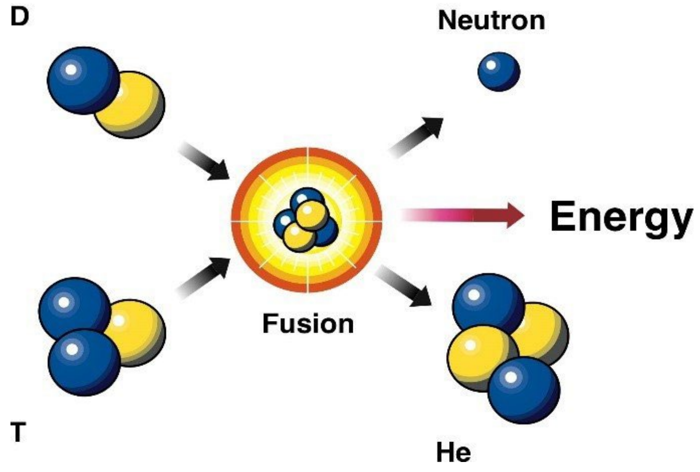
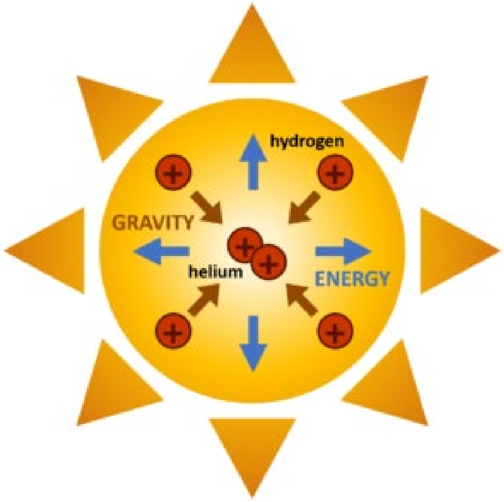
What is thermonuclear fusion?

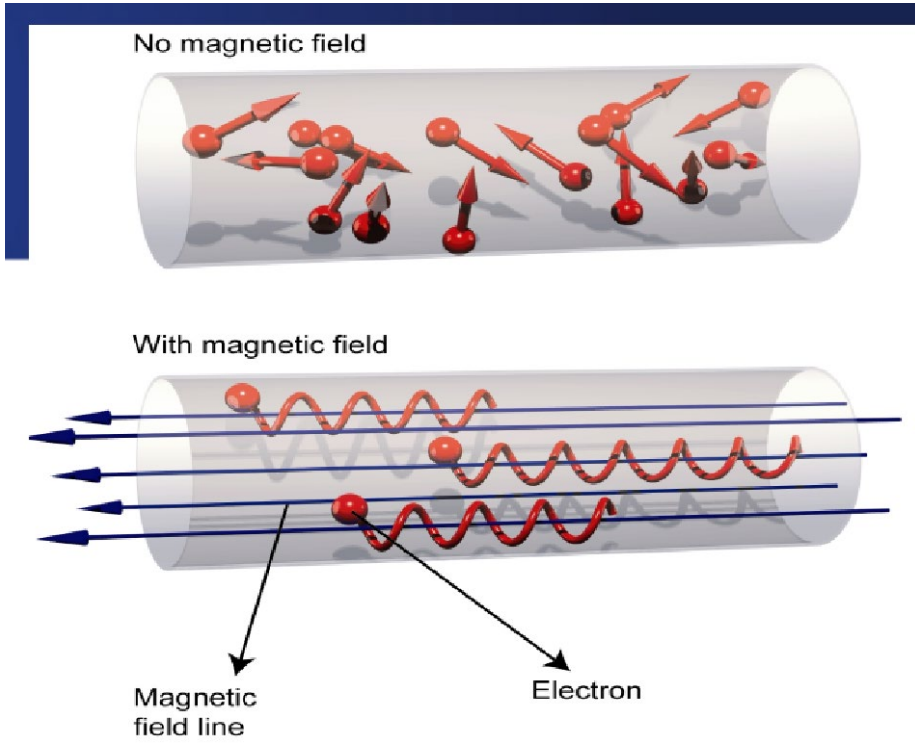
- "Thermonuclear Fusion" is the process whereby, upon reaching sufficiently high temperatures and densities, lighter nuclei combine to form heavier ones, converting a tiny amount of mass into a lot of energy (according to Einstein's $E=mc^2$ formula)

- Fusion is the engine that drives the birth, life, and death of stars in the universe, and therefore of life on Earth

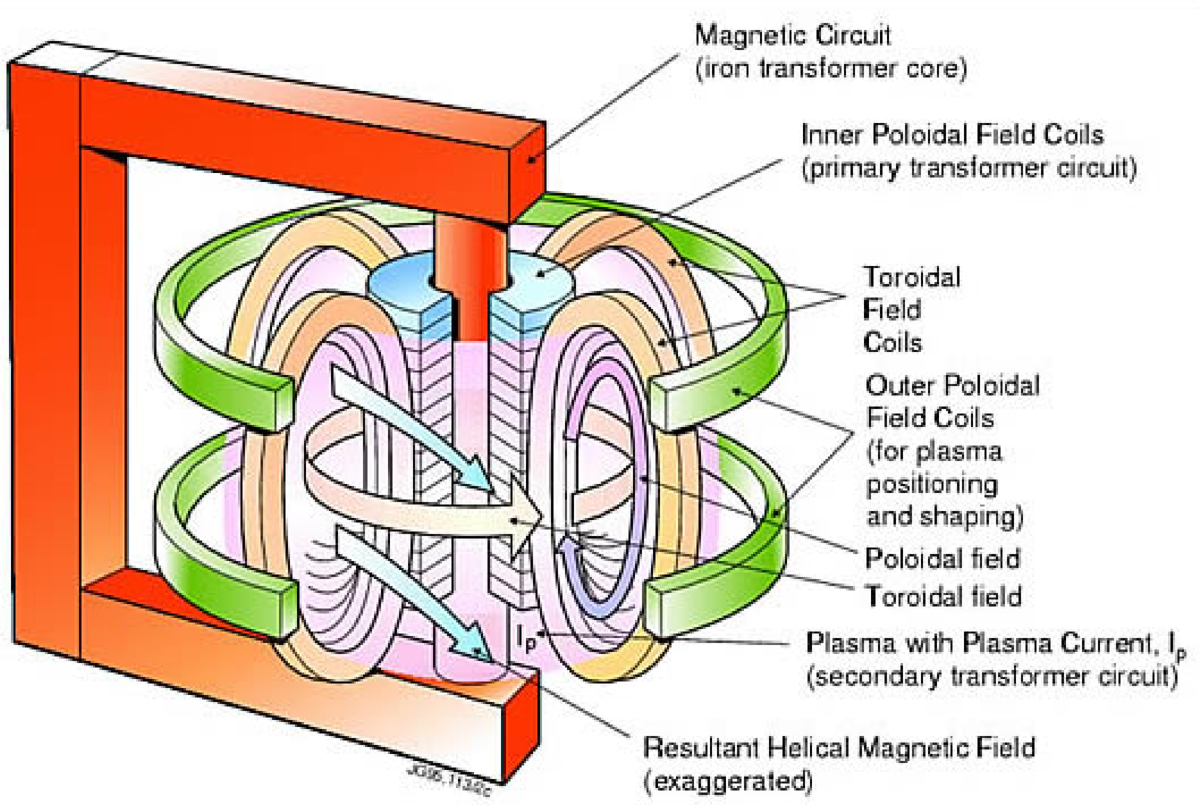




How to confine matter that hot?
With magnetic fields: Magnetic confinement

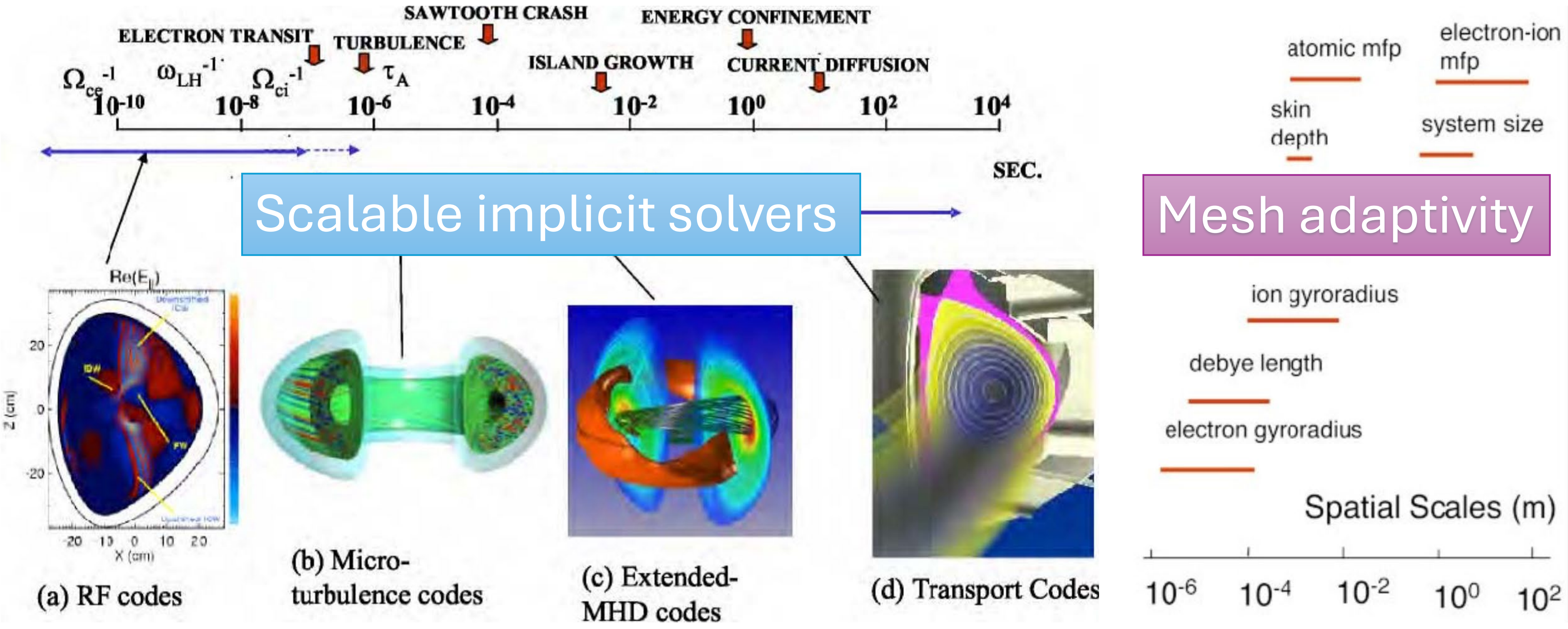


From W. Fox, PPPL

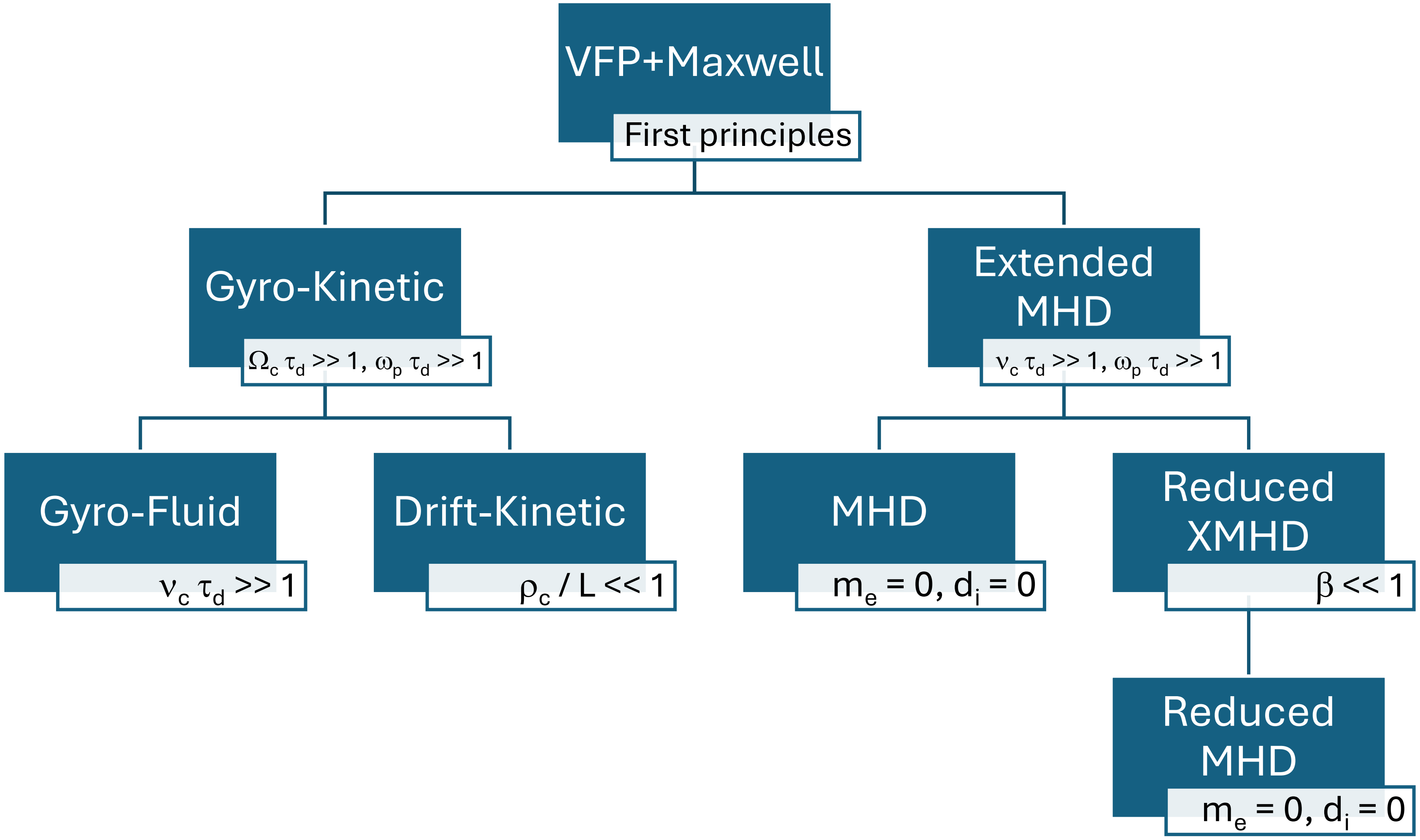


The toroidal geometry avoids end losses!

Challenges in thermonuclear fusion simulation: vast scale separations



Model hierarchy: kinetic vs fluid



Model 1:
Extended magnetohydrodynamics (MHD)

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \mathbf{J} \times \mathbf{B} + \nu \nabla^2 \mathbf{u}$$

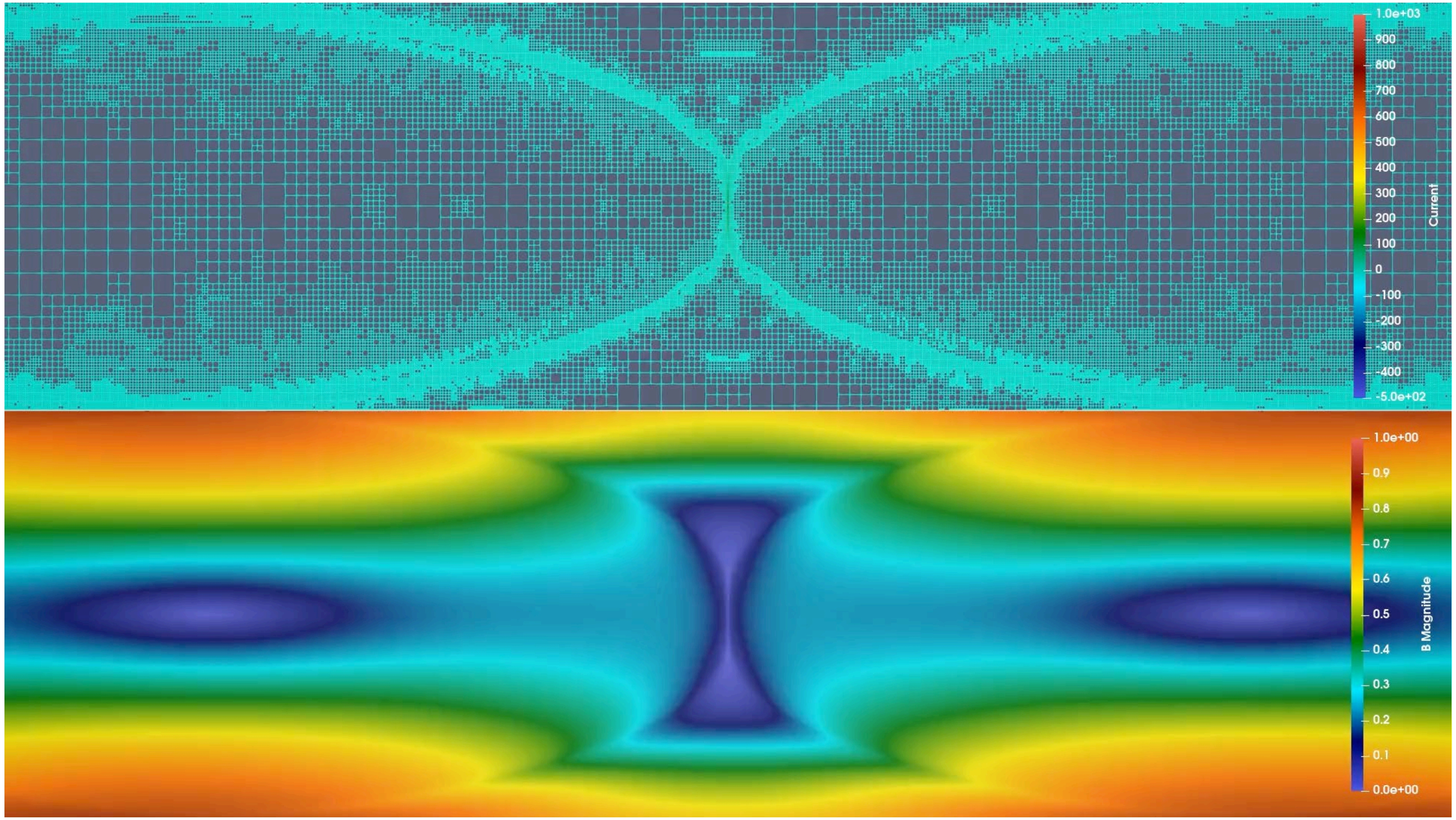
$$\frac{\partial \mathbf{B}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{B} = \mathbf{B} \cdot \nabla \mathbf{u} + \eta \nabla^2 \mathbf{B}$$

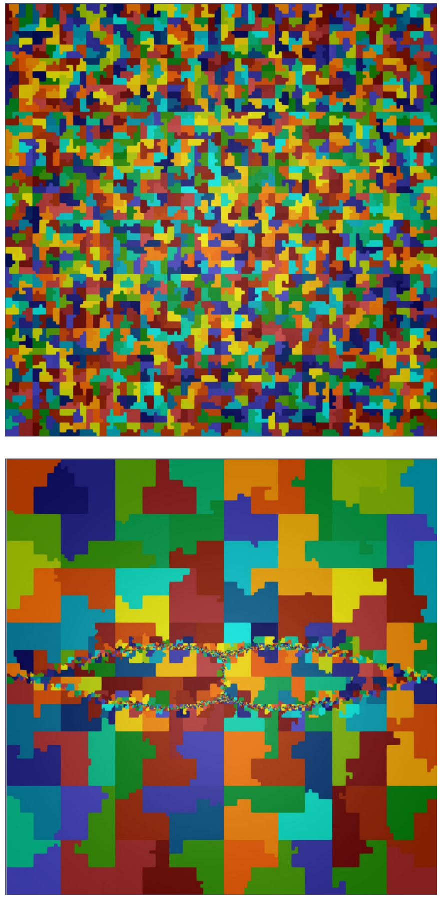
$$\nabla \cdot \mathbf{u} = 0$$

$$\nabla \cdot \mathbf{B} = 0$$

- Open-source packages used:
  - MFEM: finite element, implicit integrators, mesh adaptivity, scalability
  - PETSc: linear and nonlinear solvers for large algebraic problem
  - hypre: algebraic multigrid preconditioner
- Our solver is distributed as tds-mhd branch of MFEM (mfem.org)

Magnetic reconnection in MCF



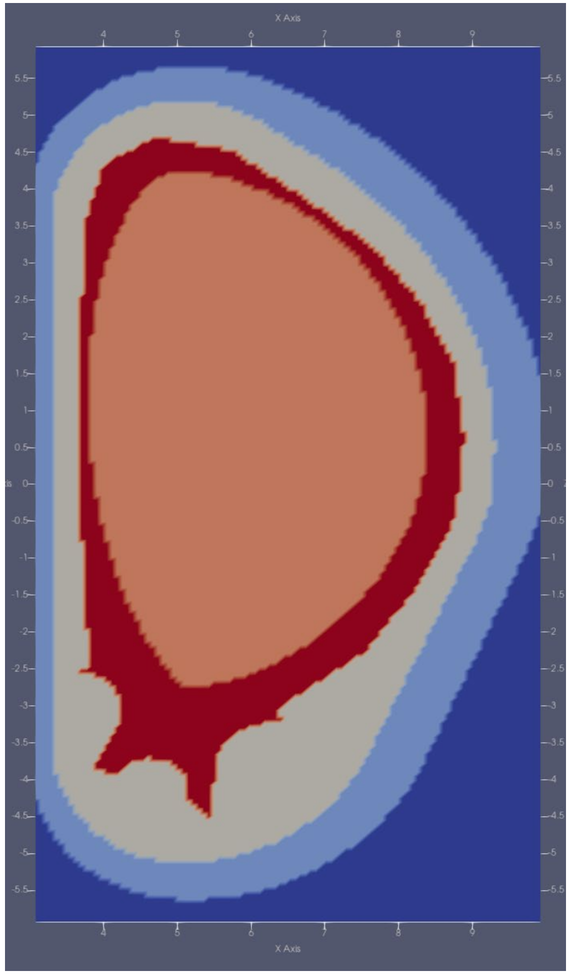


Domain decomposition
when using 1800 CPUs

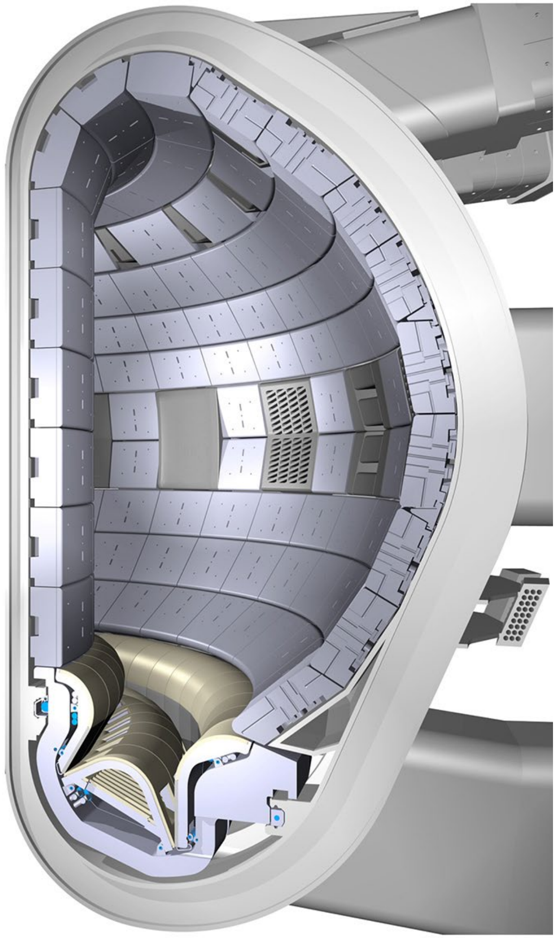
Model 2:
Quasi-static MHD with multiphysics coupling

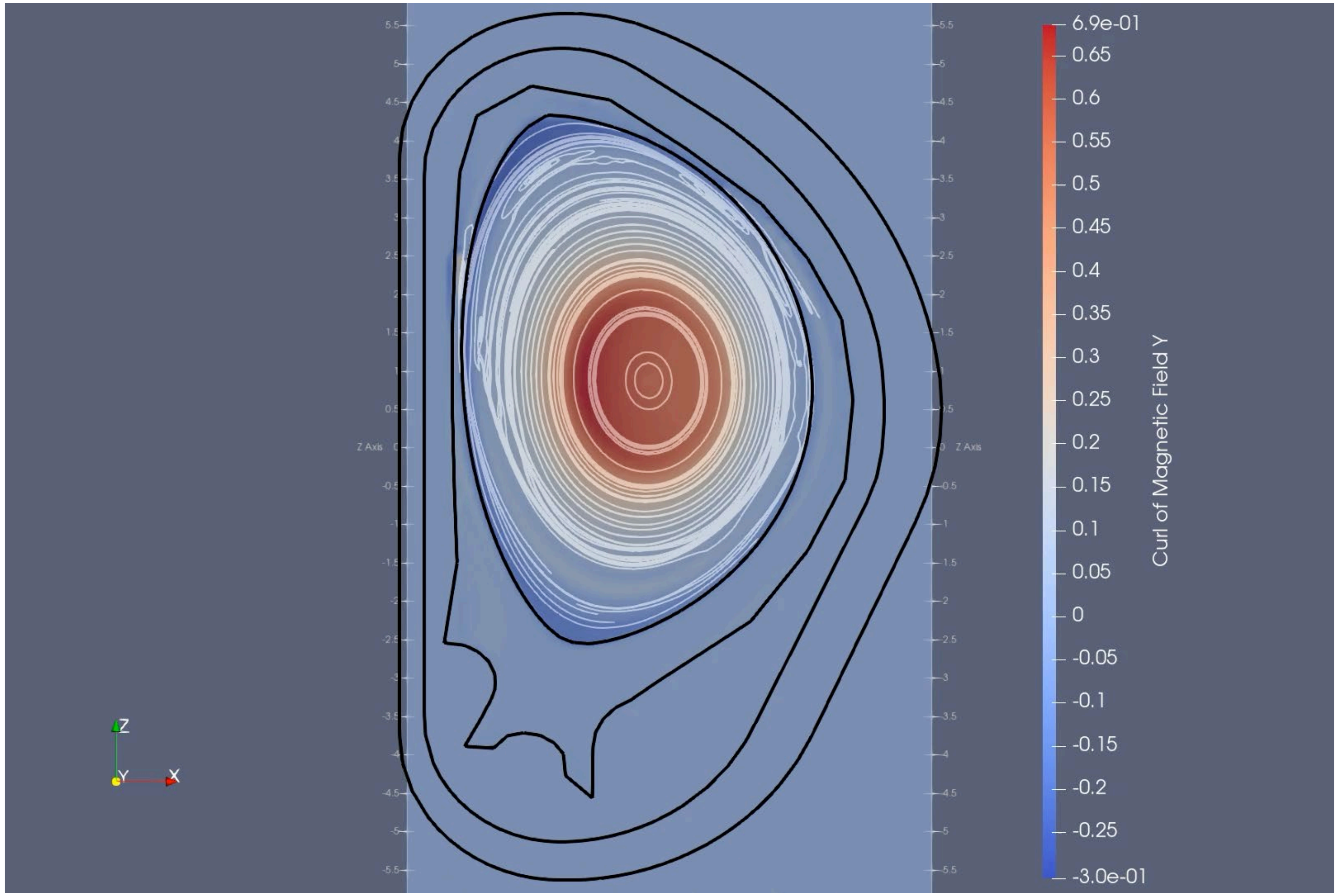
- Multiphysics coupling systems:
  - Quasi-static MHD
  - Resistive wall model
  - Vacuum

- Open-source packages used:
  - PETSc: discretization, implicit integrator, linear and nonlinear solvers
  - SuperLU: direct solver for sub-matrices



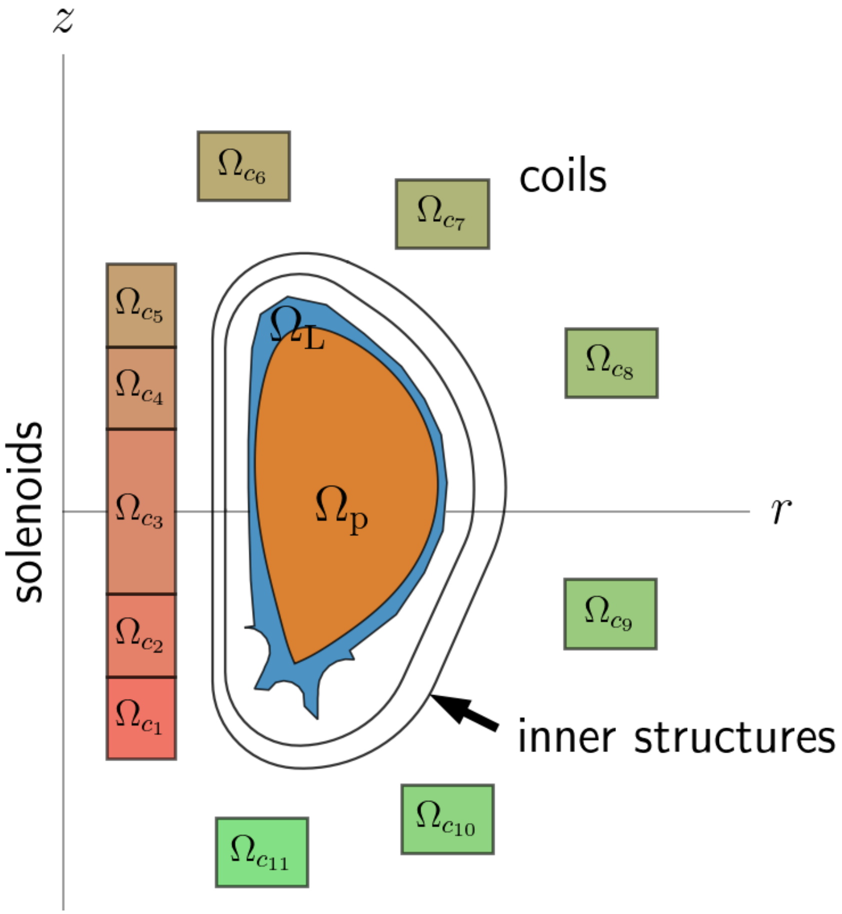
Whole device modeling for ITER



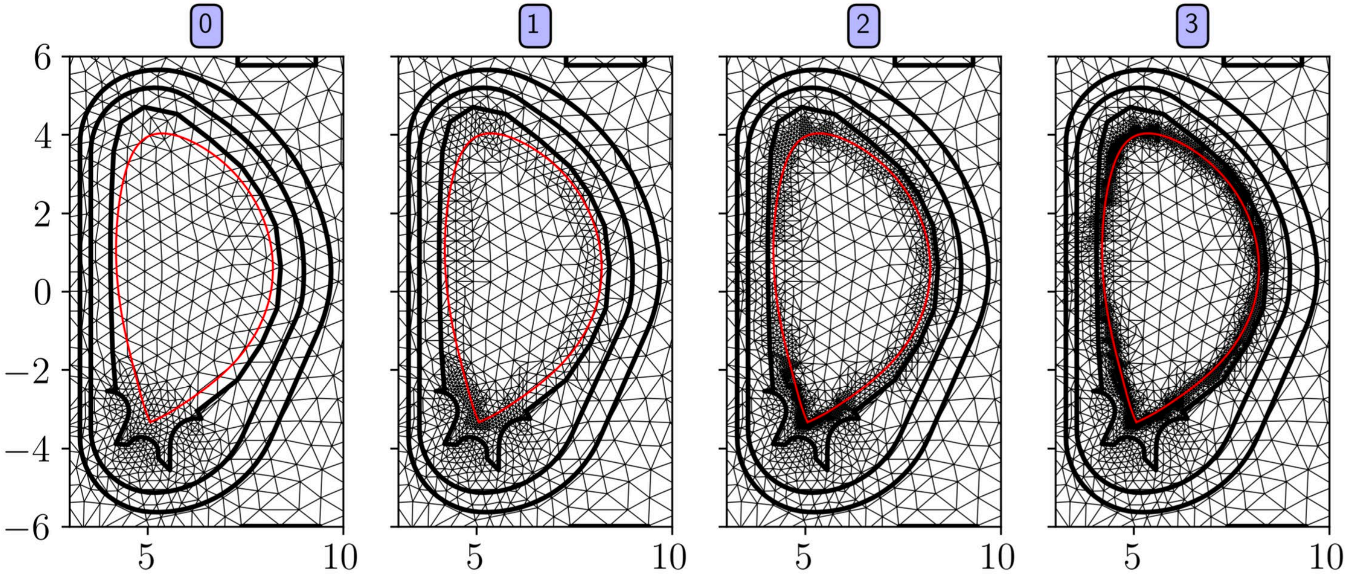


Model 3: MHD equilibrium

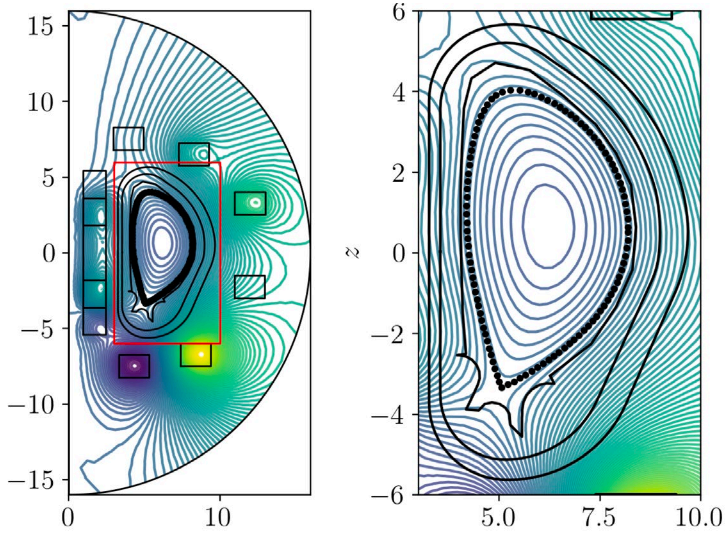
- Plasma shape optimization with force balancing by adjusting current strength
- Open-source package:
  - MFEM: finite element, linear and nonlinear solvers, meshing
- Distributed as tds-gs branch of MFEM
- We have received positive feedback from UK Atomic Energy Authority. Thanks to **the recent OSPO support**, we are refactorizing it for open-source release.



MHD equilibrium for ITER



Mesh adaptivity during the iterations



Final solution and zoomed-in

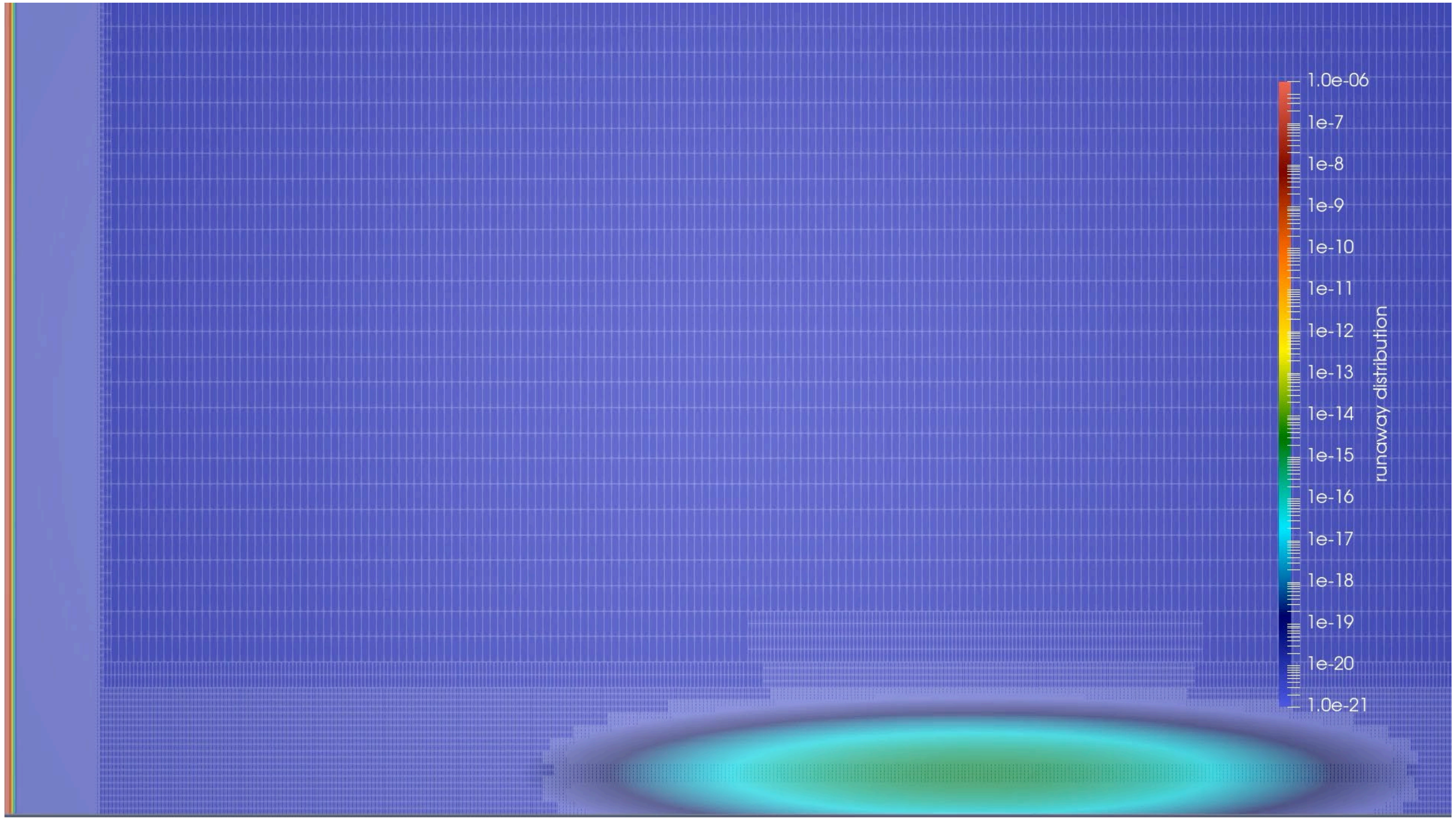
Model 4:
Drift-kinetic relativistic Fokker-Planck

- Kinetic model of strong advection and weak diffusion, used to describe high energetic electrons that can damage the device

- Open-source package used:
  - PETSc: linear and nonlinear solvers, data structure
  - p4est: mesh adaptivity
  - hypre: scalable preconditioner

- DMBF is distributed as a branch of PETSc. It is under PR review for the full release with PETSc

Interaction between high-energy tail and primary distribution



Conclusions

- Thermonuclear fusion poses great challenges in modeling and computations
- Scalable open-source packages are critical for developing modeling capabilities
- We are pushing the computational frontier towards higher fidelity simulations of fusion, by leveraging model hierarchy, scalable open-source packages, and smart algorithms on heterogenous platforms